Renewable Energy 126 (2018) 354–369

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Thermoeconomic modeling of a completely autonomous, zero-emission photovoltaic system with hydrogen storage for residential applications

Alexandros Arsalis [a, b, *], Andreas N. Alexandrou [a, b], George E. Georghiou [b, c]

[a] Department of Mechanical and Manufacturing Engineering, University of Cyprus, Nicosia, Cyprus
[b] Research Centre for Sustainable Energy (FOSS), University of Cyprus, Nicosia, Cyprus
[c] Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, Cyprus

ARTICLE INFO

Article history:
Received 27 September 2017
Received in revised form
4 January 2018
Accepted 24 March 2018
Available online 26 March 2018

Keywords:
Photovoltaic
Electrolyzer
Fuel cell
Hydrogen
Solar energy
Energy storage

ABSTRACT

In this study a completely autonomous, zero-emission photovoltaic (PV)-based system is modeled for residential applications. Apart from the PV subsystem, an electrolyzer-hydrogen storage-fuel cell subsystem is integrated to the system to fully fulfill a varying load profile throughout the year. The fuel cell and electrolyzer components are based on proton exchange membrane technology. The model allows quantification of energy and power flows, such as power input from the PV subsystem, conversion of electricity to hydrogen, and re-production of electricity. The system components are sized to satisfy demand, which is varied through a case study conducted to investigate system performance at different capacities. The economic performance of the proposed system is assessed with a detailed cost model. The proposed system (base case) results in a unit cost of electricity at 0.216 EUR/kWh for a system capacity of 100 households, which is moderately higher than the current cost of electricity in Cyprus. A parametric study including those economic parameters with a high degree of uncertainty is conducted to investigate the sensitivity and future potential of the system. The results show that the unit cost of electricity for the proposed system can be reduced below the current cost, making the system competitive, if electrolyzer/fuel cell lifetime is increased, while the specific costs of the electrolyzer and the PV are reduced.

1. Introduction

In recent years photovoltaic (PV) technology has been attracting a growing interest for various applications, due to a number of advantages and a decreasing capital cost [1]. Two PV types are currently the most promising ones for practical applications: polycrystalline silicon solar cells, which is a well-established, tested, and mature technology; and thin film solar cells, which is a relatively new technology, which can operate more efficiently than polycrystalline cells (~10%) in low-light conditions (e.g. dawn, or cloudy day) [2]. Recently, improvements in PV panel efficiency and manufacturing methods have been accomplished, while payback periods have fallen to 2–3 years for crystalline silicon systems, and to almost 1 year for some thin film PVs under moderate levels of sunshine [2]. Since PV technology offers zero greenhouse gas emissions, it is applicable for both residential and commercial buildings. Another advantage is the fact that power generation during the afternoon hours coincides with peak demand [3], with the possibility for onsite power generation, avoiding transmission losses [4]. Fuel cell technology is a promising technology for energy conversion, and can be used in two modes: either to convert hydrogen chemical energy to electrical energy, i.e. “fuel cell mode”; or to convert electrical energy to hydrogen chemical energy, i.e. “electrolyzer mode” [5]. Although regenerative fuel cells are theoretically possible [6], in practical applications separate fuel cell and electrolyzers units are usually dispatched. It has been projected that the specific cost of fuel cell technology will continue to decrease below 3 USD/W for stationary applications [7].

Since fitting residential or commercial buildings with PV panels requires grid-connection to a central grid, because supply can never match demand [8], standalone PV systems are not an option for completely autonomous systems. Grid-connected PV systems have also the disadvantage of transmission losses during import and export of power [3]. In this context, a possible solution to the

* Corresponding author. Department of Mechanical and Manufacturing Engineering, University of Cyprus, Kallipoleos 75, Nicosia 1678, Cyprus.
E-mail address: alexarsalis@gmail.com (A. Arsalis).

https://doi.org/10.1016/j.renene.2018.03.060
0960-1481/

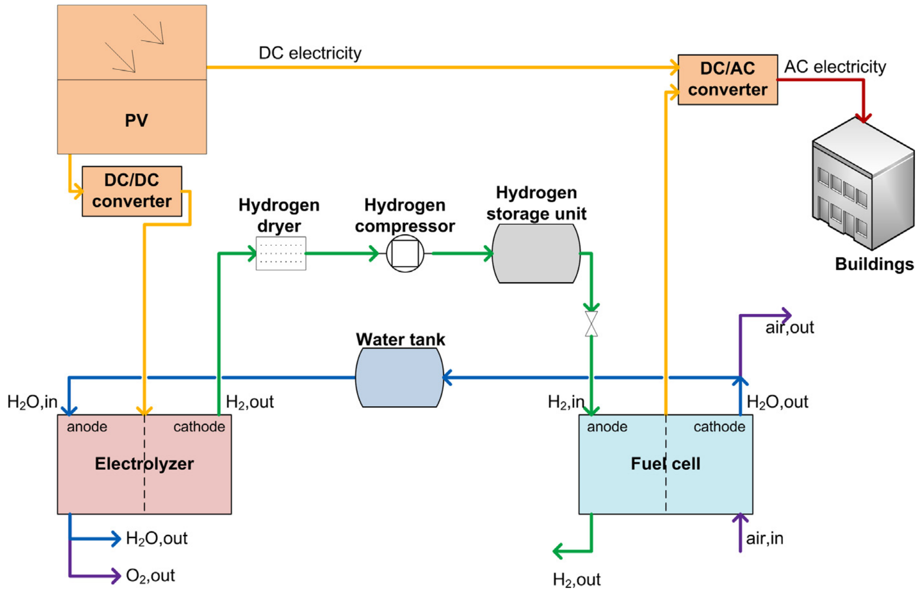

Fig. 1. Schematic representation of the proposed photovoltaic-electrolyzer-fuel cell system.

intermittence nature of PV panels is their integration with a fuel cell-based subsystem, providing conversion, storage, and re-conversion of electricity and hydrogen [9,10]. The main components in such a subsystem are: the electrolyzer (EC), the hydrogen storage unit (HSU) and the fuel cell stack (FC) [11]. The integrated photovoltaic-electrolyzer-fuel cell (PV-EC-FC) system is therefore a completely autonomous, self-sustainable, hydrocarbon-free (with zero emissions) energy system solution. Additionally the modular nature of both PV and fuel cell technologies provides the flexibility of achieving multiple system designs, capacities and configurations.

The majority of previous studies on PV-EC-FC systems have been limited to grid-connected or constant-load applications [3,12–14]. PV-fuel cell systems have also been considered for auxiliary or backup applications. Non-residential applications have been proposed in some studies, including the application of a PV-EC-FC system to a weather station, where electricity would be provided at a continuously constant load of 6.5 kW_e [3]. In a similar application a PV-fuel cell system was considered to provide electricity to off-grid radio base stations for telecom applications [12]. Another possibility is the combination of multiple types of renewable energy sources (RES), including a self-sustainable hydrogen fueling station based on both PV and wind turbine units [13], and an off-grid PV-wind turbine-hydrogen-battery system, where the RES supply energy to the system, while the battery-hydrogen subsystem is used as an energy storage device [15].

In residential applications, various configurations and approaches have been proposed. A domestic micro-grid connected to multiple grids has been proposed to fulfill residential load profile and charge electric vehicles [14]. Some studies have concentrated on the sizing method and the application of different control strategies aiming at optimum energy management [16]. A method to improve power management is the integration of batteries and supercapacitors [17]; however in a realistic application of an autonomous system, where long-term storage is required, this is usually an inadequate option. As the PV-EC-FC system has not been economically sustainable in the past, previous studies have not included detailed economic analyses, which can reveal the actual potential of these systems [18]. In some studies, RES-fuel cell systems have been coupled to heat engines (e.g. diesel generator), in an effort to meet demand while maintaining a low cost [19,20]. Also the application of a PV-EC-FC system can vary in scale; most previous work has concentrated on small-scale systems. However, in conjunction with economic performance, it may be possible to achieve lower electricity costs for larger scale systems [21].

In this research work a PV-EC-FC system is studied for potential application to a climatic area with almost constant, and continuously high, solar radiation levels. Specifically the proposed system is considered for application in Nicosia, Cyprus; the system is assumed to be isolated from the central power grid, serving the energy needs of a remote community (although this is not a restrictive application for the use of the system). The system is initially modeled for design conditions; subsequently the system components are sized to match the needs of the varying load profile. Detailed fuel cell and electrolyzer component models are modeled and integrated to the total system model. A detailed cost model is used for the economic analysis of the system. Another key factor which significantly affects the economic performance is system capacity; to determine the optimum system capacity in terms of economic performance, a case study which includes a single to multiple households is applied. Finally, a parametric study is conducted to investigate the sensitivity of the system for varying key cost parameters possessing a high degree of uncertainty.

2. System configuration

The proposed PV-EC-FC system configuration is shown schematically in Fig. 1. The PV subsystem generates DC electricity, when solar radiation is available through the PV array to fully, or partly, satisfy load demand. DC electricity is converted to AC electricity via a DC/AC converter. When PV-generated electricity exceeds load demand, excess electricity is directed through a DC/DC converter to the electrolyzer stack, where electricity is used for water electrolysis, generating hydrogen and oxygen. Generated hydrogen is stored in a hydrogen storage unit, and when load demand exceeds PV-generated electricity generation, the fuel cell stack converts hydrogen to electricity to supplement power generation.[1] To

[1] Capture and storage of oxygen is also possible, but as this would increase the complexity of the system [10], it is not considered in the configuration under study.